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Physical Impacts of Climate Change on the Western US Electricity System: A Scoping Study

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Abstract

This paper presents an exploratory study of the possible physical impacts of climate change on the electric power system, and how these impacts could be incorporated into resource planning in the Western United States. While many aspects of climate change and energy have been discussed in the literature, there has not yet been a systematic review of the relationship between specific physical effects and the quantitative analyses that are commonly used in planning studies. The core of the problem is to understand how the electric system is vulnerable to physical weather risk, and how to make use of information from climate models to characterize the way these risks may evolve over time, including a treatment of uncertainty. In this paper, to provide the necessary technical background in climate science, we present an overview of the basic physics of climate and explain some of the methodologies used in climate modeling studies, particularly the importance of emissions scenarios. We also provide a brief survey of recent climate-related studies relevant to electric system planning in the Western US. To define the institutional context, we discuss the core elements of the resource and reliability planning processes used currently by utilities and by the Western Electricity Coordinating Council. To illustrate more precisely how climate-related risk could be incorporated into modeling exercises, we discuss three idealized examples. Overall, we argue that existing methods of analysis can and should be extended to encompass the uncertainties related to future climate. While the focus here is on risk related to physical impacts, the same principles apply to a consideration of how future climate change policy decisions might impact the design and functioning of the electric grid. We conclude with some suggestions and recommendations on how to begin developing this approach within the existing electric system planning framework for the West.

Key Words: electricity, resource planning, risk assessment, climate change

1. Introduction

The awareness of climate change, and concern for its potential impacts on the electric system, are of increasing importance to policy makers and planners. A number of state governments are introducing climate plans and policies to reduce emissions and promote the development of renewable and low-carbon energy sources.[1] Regional initiatives include the Western Climate Initiative, in which signatories agree to reduce green-house gas (GHG) emissions to 15% below 2005 levels by 2020 [50], and the Western Governors Association Clean and Diversified Energy Initiative [47], with goals of an additional 30,000 megawatts (MW) of clean energy by 2015, and a 20% increase in energy efficiency by 2020. In anticipation of future state or federal policies to limit GHG emissions, some electric utilities have begun to analyze the financial implications of potential carbon regulations in their integrated resource plans [1]. Other regional planning organizations, for example the Northwest Power Conservation Council, are now incorporating policy uncertainty into their medium- and long-term plans.[2]

To date, the primary focus in most electricity policy and planning studies has been on how best to reduce the emissions associated with electricity production, and the possible economic impacts of these mitigation efforts. The question of how the electric system will have to adapt to actual changes in climate has not yet received a significant amount of attention. The lifetime of electric system infrastructure is typically one to several decades, which is long enough for climate change to impact its performance and reliability. Climate and weather define the physical environment within which the system operates, and to a certain extent existing practices reflect an adaptation to the climate conditions of the past several decades. Failure to anticipate future changes could lead to a situation where the existing practices and guidelines are no longer appropriate. The key to avoiding potentially costly problems is to understand the degree to which the power system is vulnerable to physical weather risk and to use information from climate modeling studies to estimate how these risks will evolve over time. Eventually, electric system planning and operational guidelines can be adapted as needed.

Recent news stories illustrate the vulnerability of electricity supply to the physical forces of weather. The 1998 ice-storm in eastern Canada destroyed 130 transmission towers and toppled 30,000 utility poles. At its height, blackouts affected four million people, and several weeks passed before power could be restored to some communities [28]. The 2003 heat-wave in Europe led to numerous and persistent electricity shortages caused by lack of cooling water and excessive demand, and resulted in over 30,000 deaths [42]. The California heat wave of 2006 caused over 140 deaths and numerous blackouts [7], while ongoing droughts in the southeast and in the Colorado River basin pose serious threats to both water and power supply [36, 48]. Due to a combination of floods in coal-producing regions [4], failure of rains and extreme temperatures, power shortages are now endemic across Asia.[3]

[1] Information about state-specific climate policies is compiled by the Pew Climate Center and summarized at http://www.pewclimate.org/states-regions.
[2] See the NWPPC fifth power plan at http://www.nwcouncil.org/energy/powerplan/5/Default.htm.
[3] The website www.energyshortage.org provides ongoing documentation of global energy supply problems.

Although the problem is formidable, we will argue in this paper that by building on state-of-the-art climate science and existing electric resource planning processes, it is feasible to define in concrete terms the necessity for and means of adapting to changing climate. This study can be thought of as a "pre-road-mapping" exercise, which describes the area to be mapped and suggests some analytical approaches to explore. The basis of a successful planning strategy is to understand what is known and what can be known in the near term about climate change, and to make the best possible use of this information. With this in mind, a goal of this paper is to provide an overview of climate science with emphasis on what is relevant to electric system resource planning and policy analysis.

This paper will provide a summary of the technical background needed to get a sense of what the physical risks are and how they may evolve under changing climate, how they can be represented analytically, and how they could potentially be included in electric resource planning. Physical risk refers to the probability that either electric system adequacy or reliability could be compromised by a weather event. Indirectly, changes to the physical parameters describing typical future weather may also affect the economics of different resource strategies. In estimating climate impacts, both ongoing changes to average trends and the likelihood and intensity of extreme events are important. The most significant climate variables in this context are temperature and precipitation. A list of electric power system components in the West that may be vulnerable to changes in temperature and precipitation is given in Table 1.

It is also important to acknowledge that institutional barriers and biases can make the adaptation problem more difficult than it needs to be. Electric system planning is distributed across many different entities, each of which is only mandated to consider what happens in their particular region and context. Scientifically the question of how to characterize the impact of climate change in an isolated region is ill-posed, in the sense that it does not have a unique answer. This is because each region is physically connected to a larger area, both through the climate itself and through the physical interconnections of the electric grid. To understand what may happen inside any given boundary, some information about the system outside the boundary is also required. To obtain coherent results, it is critical that the various entities engaged in resource planning use assumptions that are consistent across overlapping geographic regions.

The remainder of this paper is organized as follows: In Section 2 we provide an introduction to climate science, including a discussion of how climate modeling experiments are designed and what can be learned from them. In Section 3 we present a summary of predictions from climate models with a focus on the Western US, and summarize existing studies of the impact of climate change on the electricity system. In Section 4 we outline the basic elements of the current electric system resource planning process, focusing on those aspects that are relevant to climate. The importance of the spatial organization of the analysis and the overlap of planning activities among different entities is discussed more fully. Section 5 presents three specific examples of how to incorporate a consideration of climate risk into different elements of resource analysis. These are intended to illustrate the general approach, which largely entails the use of probability distributions and thresholds in place of point values. Finally, we provide some suggestions and recommendations for further work in this area, including a discussion of the organizational challenges.

Table 1. Vulnerability of electric system components to changes in climate variables relevant to the Western US

System Component	Temperature (T°) Increase	Precipitation Changes
Demand Side		
Annual and seasonal energy use	Decreasing diurnal temperature range implies greater energy for cooling in summer; warmer winter temperatures will decrease electricity use for heating	Increased variability; more energy may be needed to maintain conveyance and treatment of water supplies
Regional peak demand	Increasing maximum summer temperatures accelerate peak load growth due to air conditioning	Longer dry spells exacerbate high temperatures
Load duration curves	Space-conditioning load shapes may change (this may also occur due to mitigation strategies); increased transportation demand	Summer demand by the water supply system may increase (increased pumping, treatment, growth of water recycling)
Supply Side		
Hydropower production	Increasing maximum summer temperatures; increased evaporation from reservoirs; more restrictive temperature constraints for fish protection; earlier snow melt leading to reduced flows in summer and higher risk of flooding in winter	Increased year-to-year variability; lower summer flows decrease hydropower production in summer and increase fish mortality
Thermal plant efficiency	Higher maximum and average temperature leading to lower operating efficiency	Increased dry spells leading to reduced cooling water availability
T&D equipment capacity/lifetimes	Higher maximum and average temperatures imply shorter equipment lifetimes and reduced transfer capacity	No direct effect
Other Impacts		
Air quality	High temperature increases production rates of some pollutants	Increased dry spells correlate with worsening air quality
Import-export patterns	As summers warm more than winters, winter-peaking regions may become summer-peaking.	Greater uncertainty in the availability of hydropower supply for seasonal export; greater competition for summer peaking supply
Coastal infrastructure	Rising sea level, subsidence	Flood risk, storm surges

2. Overview of Climate Science

This section draws heavily on the Intergovernmental Panel on Climate Change (IPCC) fourth comprehensive assessment report (AR4), which is available online [19, 32, 38]. The IPCC was established in 1988 by the World Meteorological Association and the UN Environmental

Program to review the published literature on climate science and issue periodic assessment reports. Climate research itself is carried out by a wide variety of entities, primarily academic and governmental research organizations.

2.1 Global Climate Models

Over a dozen groups world-wide participate in the ongoing development of the atmosphere-ocean general circulation models (AOGCMs) that are used in climate science. In preparation for the fourth assessment report, the IPCC has engaged in a concerted effort to coordinate the analysis of output from different global climate models and improve the characterization of uncertainty [19, 32, 38]. Model data are archived and made available to the public through the Program for Climate Model Diagnosis and Inter-comparison.[4] Model inter-comparison studies are used both to evaluate and improve the models themselves, and to develop a more sophisticated probabilistic description of future climate for use in impact studies. The problem of how to use multiple models and multiple runs from a single model to develop objective probability distributions of future climate descriptors is now a very active research topic [2, 21].

Climate is a somewhat abstract concept, which is defined practically as the long-term average behavior of weather. In this context, long-term means 30 years or more; this is the minimum amount of time required to smooth out fluctuations due to slowly varying ocean and atmospheric patterns such as El Niño. Over very long time scales, the earth's climate is continually changing. However, over the last several thousand years, the climate had been relatively stable, until the beginning of the 20th century [38].

Although there are many complex processes involved, the basic physics underlying climate change is straightforward. The earth's climate is an open system which receives energy from the sun and re-radiates some of it back to space. Some energy is also absorbed by the biosphere, which is what powers the growth of organisms and maintains the relatively warm near-surface air and water temperatures. Human activity increases the concentration of chemically and physically active atmospheric constituents (most importantly CO2 and aerosols) and these in turn alter the rate at which energy is re-radiated to space. Under current conditions, rising CO2 levels lower the energy being re-radiated [14], leading to a slow increase of the total energy contained in the atmosphere. A build-up of energy implies an increase in the average air temperature, *a.k.a.* global warming. It also implies an increase in the energy contained in atmospheric fluctuations, which translates to more intense weather systems. Hence, there is no contradiction between global warming and episodes of unusually cold weather in some regions. These predictions follow from basic thermodynamics and the physics of radiation balance, and were made prior to any observations of global average temperature increase [44]. Warming trends have subsequently been confirmed by observation and are consistent with more detailed predictions from the models [25].

Fundamental physics provides a basic understanding of the earth's response to changes in the composition of the atmosphere; global climate models are needed to assess how much and how

[4] The project web site is http://www-pcmdi.llnl.gov.

quickly different effects will occur. The use of global climate models is somewhat different from the modeling techniques used in energy planning and forecasting. In particular, climate scientists often use models as a form of controlled experiment, to improve their understanding of how the climate responds to different types of perturbation. Widely varying processes can be compared by determining how much they contribute to radiation flux changes, quantified by assigning a *radiative forcing* value to each. This forcing is the product of an intensity (i.e., force per unit mass of the constituent) multiplied by the quantity of the constituent in the atmosphere. The forcing has the units of watts per square-meter and represents an addition or subtraction to the net energy flux due to the process in question. The numerically largest forcing is from emissions of CO2 produced by combustion of fossil fuels. Methane (CH4), nitrous oxide (N2O) and aerosols are also significant.

AOGCMs are enormously complex, and the spatial resolution that can be achieved in the model is determined by current limits on available computer memory and speed. This means that processes that occur at spatial scales smaller than a single grid cell must be represented by some kind of averaged set of equations. It also limits the degree of accuracy in representations of land or ocean bottom topography and land surface cover. Different models use different strategies for deriving and parameterizing these averaged descriptions of smaller-scale physics, which in turn lead to different predictions for future climate. For temperature, which tends to vary smoothly with location, this is not a big problem and most models give consistent results for temperature predictions. Results related to the water cycle show more variability between models.

Water cycle refers to the movement of water (in the liquid, vapor[5] or frozen state) between the atmosphere, oceans and land surface. The major components of the water cycle are evaporation and precipitation. The capacity of the atmosphere to hold water increases with temperature, but the actual amount of water it will contain is constrained by the fact that evaporation requires energy. The energy and mass balance that determine humidity and precipitation can be reasonably well-represented on average by an AOGCM, but the details that determine actual precipitation events must be parameterized. As precipitation is more sensitive than temperature to relatively small scale features (e.g., presence of mountains), the AOGCMs do not do as well at capturing the distribution of precipitation events, and there may be biases in the predictions for mean precipitation. Given the strong relationship between humidity and atmospheric heat content, models that show different behavior in the water cycle will also show somewhat different predictions for mean temperature increase. The bottom line is that different AOGCMs produce somewhat different future climates, loosely characterized as warm/wet *vs.* (relatively) cool/dry.[6] As there is not yet a good basis for claiming that one set of parameterizations is better than another, typically the full range of predictions from different AOGCMs is used to characterize potential future climate.

[5]Some authors refer to water vapor as a greenhouse gas (GHG) because atmospheric water vapor affects the global energy balance. This terminology can be misleading as GHGs are usually identified with pollutant emissions. Water vapor is not an emission in this sense; the amount of water in the atmosphere is determined by climate feedbacks.
[6] In this context, cool is relative and is still warmer than recent historical climate.

2.2 The Role of Emissions Scenarios

Because climate change is driven by emissions, a model run requires a detailed *emissions scenario* to be specified for the entire simulation period. The simulation will typically begin in the pre-industrial past, and use estimates of historical emissions and land-use change to "spin-up" the model to the present-day climate. Future emissions are handled differently depending on whether the modeling goal is to perform an equilibrium experiment or a transient experiment. In equilibrium experiments, a specified change to some atmospheric constituent (e.g., a doubling of CO_2) is imposed and the model is run until the system comes to a new equilibrium. This type of experiment is used to quantify the climate forcing associated with different processes. It has also been used to estimate the widely quoted *climate sensitivity*, which is defined as the mean global temperature increase associated with a doubling of CO_2 from pre-industrial levels. The IPCC cites a best estimate for climate sensitivity of 3 degrees Celsius (°C) with a likely range of 2 to 4.5 °C. The multi-model distribution is asymmetric, so much higher values are possible, but much lower values are very unlikely [38]. Climate sensitivity is a measure of the global average response of the climate to a set of forcings, and the computed ranges on sensitivity are *not* predictions of what the temperature change will be in the future.

Transient experiments are intended to mimic the more realistic situation of continuously changing emissions. In a typical set-up, CO_2 concentrations are increased by 1% per year. The *transient climate response* (TCR), which is defined as the global average temperature change at the time of CO_2 doubling, is used to quantify the change to the climate. This number can also be used as a model inter-comparison metric. There is less spread in predictions of TCR than for climate sensitivity, due in part to the fact that it is more constrained by observational data [10]. This type of experiment is somewhat closer to a forecast, as historically emissions growth is comparable to 1% per year. However, these experiments may not account for all the other significant emissions and land-surface changes that have occurred to date. Moreover, there is no particular reason to believe that emissions will continue to grow at the same rate indefinitely. Thus, while transient experiments provide a better estimate of the time-dependent response of the climate system, they should not be used as forecasts.

In an effort to develop emissions scenarios more closely related to actual human activity, the IPCC published a *Special Report on Emissions Scenarios* (SRES) in 2000 [29]. In this report, a number of possible futures were outlined using different assumptions about global economic growth, technology change, and political and social priorities. These were intended to explore a plausible range of possibilities, and cannot be objectively characterized as more or less likely, *i.e.* they do not in any sense represent a forecast of future emissions. Recent data show that actual emissions growth since 2000 exceeds the highest-growth scenario developed in the SRES [33].

Recently, modelers have begun to explore so-called *stabilization scenarios*. In this situation, the idea is to invert the problem, and deduce the emissions level that would be required to keep future climate change within some given range. Currently, a long-term change of 2 °C is considered to be the upper bound if severe disruptions are to be avoided, although this may change as a better understanding of climate feedbacks develops [15]. To limit the global mean temperature increase to 2 °C or less would require emissions that are well below the lowest scenario developed in the SRES [15, 22, 45].

The stabilization approach is useful in providing a benchmark against which human activity can be compared, but it is important to bear in mind that these modeling concepts are not predictions. Climate stabilization cannot occur until CO2 and other constituent concentrations level off; as long as emissions are non-zero, these concentrations can continue to grow. Global models show unanimous agreement that ongoing climate change affects the cycling of carbon between the land, oceans and atmosphere, so that an increasingly large fraction of emitted CO2 will stay in the atmosphere under a warmer climate [25]. As the atmosphere heats up, the ocean begins to absorb some of the excess energy, but at a very slow rate. The slow ocean response means that the length of time necessary for the system to come to a new equilibrium could be decades or centuries, depending on the details of the forcing [13]. This also means that even if emissions drop to zero tomorrow, the climate will continue to change as the existing energy imbalance works its way through the system [14]. Recent studies suggest that anything less than a 60% reduction in emissions by 2050 will produce a temperature increase of 2 °C at 2100. Even a 90% drop by 2050 may not prevent climate change from eventually reaching this level [22, 45].

For public policy purposes, the usefulness of stabilization scenarios depends in part on accurate estimation of climate sensitivity, which is subject to large uncertainties [10, 34]. Alternative targets, (e.g., emissions trajectories with larger near term growth and faster drop-off in the medium to long term) may be both more practical to implement and easier to model physically [10]. The climate impacts of permanent cuts in emissions may not be clearly discernible in the short term, and the notion of “safe” levels is very likely to continue to evolve [16]. Hence, effective long-term electric system resource planning requires an analytical framework that clarifies the relationship between climate variables and planning variables, and allows for changes to regulatory or operational constraints during the planning period.

2.3 Recent Results from Climate Models for the Continental U.S.

The findings of the IPCC fourth assessment (AR4) are summarized and described in the Synthesis Report [19]. Observations of global average air temperature and sea-surface temperatures agree well with model predictions. Other, more subtle changes are now being observed and in fact are occurring more quickly than was anticipated [19, 32, 36, 39, 53]. These include the earlier growth of plants in spring, changes in the habitat range of climate-sensitive species, and rapid loss of arctic sea ice.

Better understanding of the role of diverse pollutants and aerosols has helped improve predictions of changes to precipitation, but these still remain quite variable between AOGCMs. In general, a warmer atmosphere holds more water, but how this affects precipitation depends strongly on regional topography and weather patterns. Regionally, climate models tend to show an enhancement of extremes, with dry areas becoming drier and wet areas becoming wetter. Precipitation is likely to be more uneven, with more intense rainfall events separated by longer dry periods in between. In areas where precipitation decreases on average, reduced soil moisture can contribute to raising local temperatures further above the mean. Models and observations both show larger warming over land than over the oceans, which may affect the large-scale atmospheric systems in the Pacific that influence seasonal precipitation patterns in western North America [25].

A summary of potential changes related to temperature and precipitation is given in Table 2, along with the estimated likelihood when this is defined in the IPCC's fourth assessment. The IPCC has issued guidelines for defining likelihood and confidence levels for both observations and model results. For model data, likelihoods are based on how often a set of AOGCMs predict the same result over an ensemble of model simulations. *Likely* corresponds to a 2-out-of-3 chance (66%) and *very likely* to a 9-out-of-10 chance (90%) [19, 25].

Table 2. Projected changes to temperature and precipitation over the Continental U.S.

Climate Variable	Predicted Effect	Likelihood
Annual Temperatures	Mid-latitude temperatures increase above global average; decrease in diurnal temperature range; less warming over oceans than over land	Very Likely
Summer Temperatures	Largest warming in the southwest; maximum temperatures increase more than average temperatures	Very Likely
Heat Waves	Longer, more intense and more frequent	Likely
Winter Temperatures	Minimum temperatures increase more than averages; decrease in length of snow season	Very Likely
Cold Spells	Decrease in frequency, intensity and duration	Very Likely
Summer Precipitation	Decrease in western US; substantial decrease in southwest US and Mexico	Likely
Winter Precipitation	Increase except in southwest US and Mexico; decrease in snow depth	Likely
Drought	Longer droughts, especially in the southwestern US	Not given
Extreme Rainfall	More intense rainfall events; greater variability	Not given

A number of more detailed studies that focus on the western US support the predictions cited in Table 2 [12, 17, 30, 31, 36, 37, 40]. The most significant general trends are warmer temperatures in all regions of the US and increased aridity in the southwestern US. Warmer winters can have a strong effect on water supply. Regional climate studies consistently show a decrease in total snow pack, earlier snowmelt in spring, delayed autumn snowfall, less precipitation in shoulder months, and an increase in extreme precipitation events and risk of flooding. Because snow pack acts as a "virtual reservoir," these findings may have serious implications for water management and hydropower in the Western U.S. [6, 36]. A detailed review of AOGCM output and observational data for the southwestern US [37] finds that substantial drying is predicted by all models, and may already be underway. While past instances of drought (such as the dustbowl of the 1930s) have been related to La Niña events, the drying predicted for the near future is due to entirely different physical processes, and will therefore enhance any La Niña-related events. These effects may be large enough to have a negative impact on continued demographic growth in the region [36].

3. Climate Change Impact Studies

Climate change impact studies generally require information at smaller spatial and time scales than are available from AOGCMs. This problem is handled by a procedure known as *down-scaling*, in which AOGCM output at larger scales are used to develop predictions of climate variables at smaller scales. There are two general approaches: (1) regional climate models [23, 38] and (2) statistical down-scaling methods [38, 49].

Regional climate models (RCMs) fully simulate the climate in a smaller region using data from AOGCMs to supply values for the climate variables at the region boundaries [23]. The spatial area modeled by an RCM is typically continental-scale, so these models are computer-intensive and can be as complicated to develop, use and validate as AOGCMs [25]. A number of regional scientific organizations have been created to collaborate on RCM development. The North American Regional Climate Change Assessment Program (NARCCAP) is undertaking the integration of a number of high-resolution RCMs to provide detailed simulation output for the U. S. and Canada, and a systematic assessment of regional model uncertainties.[7]

Statistical down-scaling methods (SDM) are simpler to develop and can be tailored to a given application. An SDM analysis uses historical data to determine a quantitative relationship between a given set of climate variables and the quantity of interest. For example, historical data can be used to relate the temperature averaged over a given spatial area (which would be chosen to be comparable to an AOGCM grid cell or cells) to the temperature at a specific location within that area. Time series of the AOGCM temperature data can then be used to predict future local temperatures, which in turn can be used to estimate potential local impacts.

Impact studies must be carefully designed to properly account for intrinsic weather variability. Because the climate system is turbulent, the time series of future climate predicted by a given AOGMC and emissions scenario will also depend on the data used to initialize the model. Such variability would exist even if the models were perfect. This is handled in practice by taking several *model runs,* which are simulations using a given AOGCM and emissions scenario that have been initialized with different data, and averaging the impacts across these runs. The uncertainty due to modeling imperfections is estimated by comparing the results calculated for different AOGCMs and emissions scenarios. Averaging the results of different model runs will smooth out some of the natural variability, and depending on the application it may be appropriate to average at different stages of the analysis. This problem is not unique to climate: for example, the projections of economic growth used in load forecasting do not attempt to anticipate specific booms and busts, even though these clearly have important effects on load growth year-to-year.

A variety of regional climate studies concerned with the western US region have been published. The state of California has been particularly active in this area.[8] For the Western US, a major

[7] Information on this program is available at http://www.narccap.ucar.edu/index.html.
[8] Executive Order S-3-05, issued in June 2005, directs the Secretary of the California Environmental Protection Agency to report biannually on global warming impacts to water supply, public health, agriculture, the coastline, forestry, and on mitigation and adaptation plans.

focus is water supply and related hydropower impacts. Other studies have examined the frequency and intensity of heat waves and droughts, impacts on air quality and related health effects, transmission of infectious diseases, and extreme events such as flooding and wildfires. A list of recent studies, which is representative but not exhaustive, is given in Table 3. Table 3 includes only physical impact studies; many analyses of the potential for mitigating GHG emissions and the related economic costs and benefits have also been published. In Table 3, the Scenarios column indicates which SRES scenarios were used to drive the global models that provide climate data for the impacts analysis. High, medium and low refer to the relative level of total emissions in each scenario. The "Doubled CO2" scenario refers to a modeling exercise in which the amount of CO2 in the atmosphere is doubled, and the climate model runs until the climate reaches a new equilibrium. Typically, impact studies also use results from several different AOGCMs, which contributes to the spread in results.

Table 3. Summary of western region general climate impact studies.

Study	Region	Scenarios	Subject	Conclusions
Hayhoe *et al.* 2004 [17]	California	A1FI, B1 (high, low)	Heat waves, snow pack	Frequency of heat waves in Los Angeles increases by 4 times (B1) to 6-8 times (A1FI); snow pack decreases by 30-70% (B1) to 73-90% (A1FI)
Cayan *et al.* 2005 [6]	California	A2, B1 (medium, low)	California climatology changes	Summer temperature increases of 0.6-2.1 °C by 2035; 1.7-3.4 °C by 2070; 1.6-6.4 °C by 2100. Winter temperature increases are somewhat smaller and lie in a narrower range.
Dreschler *et al.* 2005 [9]	California	A1FI, A2, B1 (high, medium, low)	Air Quality; Public Health	Acclimatization can moderate the public health effects of heat waves but implies a large increase in air-conditioning demand; ozone may increase by 4-20 ppb by 2100 (current regulatory standard is 70 ppb).
Steiner *et al.* 2005 [40]	California	Doubled CO2	Air Quality	Simulations predict that ozone will increase 3–10% in various regions of California; this may be mitigated by stricter emissions standards.
Mote *et al.* 2006 [27]	Pacific Northwest	A2, B1 (medium, low)	Regional climatology changes	Growth in summer temperatures exceeds growth in winter temperatures; total annual precipitation may not change but earlier peak flow will reduce hydropower; no clear trend in wind potential
Northwest Power Conservation Council ISAB 2007 [31]	Pacific Northwest	Various (literature review)	Columbia River Basin Ecology	More precipitation falls as rain; smaller snow pack; higher water temperatures especially in summer; higher winter river flows, lower summer flows; increases in wild fires; loss of salmonid habitat; loss of forest due to drought and pests
Seager et al. 2007 [37]	Southwest	A1B (medium)	Precipitation changes	Transition to a more arid climate is likely underway; drought conditions may become the new regional climate normal within decades

3.1 Electricity-Related Climate Impact Studies

As the primary drivers of climate change are emissions from the burning of fossil fuels, to date most of the studies relating climate and electricity have focused on mitigation measures such as the deployment of new technologies to reduce emissions. McCann *et al.* [24] present an overview of the current regulatory and management practices of various entities involved in electric system planning and operations in California and discuss how various mitigation strategies might play out in this context. They also note the importance of including California's relations with neighboring states in both technical and policy analysis. Studies that look explicitly at how particular climate or weather variables influence electricity production and use are less common. Table 4 presents a reasonably complete list (for some studies, the climate scenarios are described in terms of the resulting average temperature change (ΔT), which is noted in Table 4).

Table 4. Summary of energy-related climate change impact studies.

Study	Region	Scenarios	Subject	Conclusions
Sailor 2001 [35]	8 states including CA, WA	Doubled CO2	Electricity consumption	Increase of 10% in CA due to cooling demand; small net decrease in WA due to decreased heating demand.
Breslow & Sailor 2002 [5]	U. S.	A1B (medium)	Wind speed	Reduced wind speeds of 1-3.2% by 2050; further reduction of 1.4-4.5% in 2050-2100, but the uncertainty in the later period is large.
Pan et al. 2004 [59]	U. S.	1% per year increase in CO2	Solar Irradiance	Exploratory study shows on the order of 5-10% reduction in solar irradiance averaged over 2040-2050; varies seasonally and regionally
NWPPC 2005 [30]	Columbia River Basin	1% per year increase in CO2 [58]	Hydropower	Winter and spring hydropower generation increases; summer hydropower decreases; decreased winter heating demand; increased summer loads; changes to timing of peak flow will affect flood control schedules
Hadley et al. 2006 [51]	U. S.	ΔT=1.2°C and ΔT=3.4°C	Energy use for heating and cooling	The increased energy required for cooling is larger than the decrease in energy required for heating.
Franco & Sanstad 2006 [11]	California	A1FI, A2, B1 (high, medium, low)	Peak load and electricity consumption	Based on historical data for California, expected climate-induced load growth for 2005-2034 is 1.2-3.9% for consumption and 1.0-4.8% for peak demand.
Vicuna et al. 2006 [52]	California Upper American River	A2, B1 (medium, low)	Hydropower	Hydropower generation and revenues drop under all scenarios; effects are difficult to generalize due to importance of reservoir size and operation rules.
Miller *et al.* 2007 [26]	California	A1FI, A2, B1 (high, medium, low)	Extreme heat and electricity demand	Extreme heat days (defined as 1-in-10 exceedance under the current climate) increase by up to 200% inland and 400% in coastal regions by 2100. The A1FI scenario produces 20-30% more extreme heat days than the B1 scenario. For current system conditions these weather events lead to 17% demand shortfall.
Thatcher 2007 [41]	Australia	ΔT=1.°C	Load duration curves	Changes to load duration curves given a change in local average temperature were estimated for four locations in Australia.
US CCSP 2007 [43]	U. S.	Literature review	Energy use in buildings; production technologies	Increased energy for cooling and decrease for heating; on balance there is a net increase in most regions; increase in thermal supply constraints due to lack of cooling water

The U.S. Climate Change Science Program has recently published a literature review of climate impacts on energy for the US [43]. This review notes that energy consumption in buildings has received some attention, but information on other sectors (e.g. industry) and the potential impacts on energy production, is still quite limited. On the supply-side, there have been isolated studies of water supply for cooling of thermal power plants, temperature effects on thermoelectric power generation efficiencies, and potential impacts on wind power potential and on hydropower production.

Studies that focus on the demand-side have looked primarily at energy consumption for space conditioning [35, 41, 43] and peak electricity demand as it relates to local temperature [11, 26]. Space-conditioning energy use is generally assumed to scale with heating and cooling degree-days (HDD/CDD). It is fairly straightforward to develop projections of HDD and CDD under different climate scenarios and use regression-based models to infer the corresponding change in space-conditioning energy demand. In summer-peaking regions, there is an observable relationship in historical data between peak system loads and high temperatures, which can similarly be used to extrapolate a climate-induced growth in peak load under different scenarios [11, 26, 32].

These analyses are useful in that they demonstrate the feasibility of an approach, and provide some idea of the potential order of magnitude of climate impacts, but they cannot provide quantitative inputs into electricity resource planning without some methodological improvements. For example, the representations of electricity demand are generally too crude to be used in current resource planning analyses, and the question of which climate variables serve as the best predictors of electric system impacts has not been examined systematically. The choice of which scenarios to use also seems somewhat arbitrary and no discussion of how to associate a probability or likelihood with any of the results has been given. This is essential if a quantitative assessment of physical climate risk is to be included in electric system resource planning.

The problem of how to use multiple models and multiple runs to develop objective probability distributions of future climate descriptors is now an active research topic [21, 25, 32]. The basic idea is to use the relative success with which an AOGCM is able to predict past climate to assign a weight, which can then be used to develop a probability distribution for the results from a set of models. There has also been progress in improving the predictability of extreme events [2, 54]. These efforts do not solve the problem of how to decide whether an emissions scenario is plausible; future emissions depend on social, political and economic factors that lie outside the bounds of climate science proper. However, given the long adjustment times in the climate system, most emissions scenarios produce similar results for the first few decades of a simulation [25, 45]. Model results for this early period are also more constrained by historical data [10], and will obviously be less sensitive to differences in how long-term feedbacks are modeled. The time scale of ten to thirty years is also the most relevant for infrastructure planning. Impact analyses oriented towards this time frame would therefore be worth pursuing.

4. Electric Resource Planning: Overview of Current Practice

As electric system analysts already use sophisticated methods to forecast load and resource requirements, and to account to some extent for weather variability, it seems logical to develop representations of future climate to fit into this existing framework. One challenge that arises is that planning activities are distributed across several types of organizations, which also operate at different spatial scales (e.g., a load serving entity (LSE) may operate within a single county, whereas a balancing authority or grid operator may cover several states). It is extremely important in representing climate effects to preserve the real spatial correlations that exist in weather systems. This imposes a constraint on the modeling activities of all system members.

To provide context for these institutional issues, in this section we provide a brief overview of some existing planning processes in the West at the regional scale and for a representative system member. Regional scale system planning is illustrated using some current activities of the Western Electricity Coordinating Council (WECC) [46, 55, 56], while our description of a system member is based on a typical integrated resource plan (IRP) [1, 3, 18]. Here we emphasize the importance of the spatial organization of the analysis. In Section 5 we present some suggestions of how to incorporate climate risk into actual modeling exercises.

4.1 Electric System Planning Processes in the Western U.S.

Different types of organizations within the Western US conduct long-term electric system planning. At the most localized level, utilities in many states periodically prepare long-term resource plans, often referred to as *integrated resource plans* (IRPs), which are submitted to and reviewed by state regulators. These plans serve to identify the utility's future resource needs – typically looking out over a period of ten to twenty years – and identify a portfolio of supply- and demand-side resources to meet those needs. Total cost is the primary metric used to evaluate different candidate portfolios. Uncertainties are often evaluated through some combination of scenario and contingency analyses. For example, utility IRPs may incorporate a base-case load forecast and several alternative load forecasts to account for uncertainty in demographic variables and weather-sensitive loads. In areas with significant hydropower generation, IRPs may include probabilistic distributions of annual rainfall derived from historical data. Evaluation of the economics of future resource additions under different scenarios helps define the potential trade-offs between lower total cost and reduced cost uncertainty. Some utilities also evaluate carbon regulatory risk, represented as an increased cost associated with carbon-emitting fuels, which will affect the selection of generation resources that make up the least-cost portfolio [1].

Transmission planning is typically conducted outside of the utility IRP process, and occurs at multiple levels. Individual utilities or groups of utilities within a common region conduct stand-alone planning studies to evaluate the economics of specific transmission expansion projects. At the regional level, the WECC's Transmission Expansion Planning and Policy Committee (TEPPC) conducts and coordinates transmission-related planning analyses. TEPPC studies use a production cost model to look at system congestion and assess the impacts of transmission expansion projects, large-scale deployment of new renewable generation capacity [55] and other regional-scale infrastructure projects. In support of these activities, the TEPPC maintains a public database of information on generation resources in the WECC area.

The WECC Load and Resources Subcommittee (LRS) undertakes resource adequacy studies at the regional level [46, 56]. The primary focus is on whether planned resources are sufficient to meet expected peak loads and annual energy needs over the analysis period. LRS studies use data collected from Balancing Authorities, including ten-year forecasts of monthly peak demand, annual energy, generation additions *etc.* The LRS uses a relatively simple network model[9] of the transmission system, with 26 "bubbles" representing load centers connected by major transmission links. The LRS produces several types of studies, including the Power Supply Assessment which looks out over a ten-year time frame, the Long Term Resource Assessment, and seasonal assessments [56]. These studies may include different types of scenarios and sensitivity analyses. For example, the load forecasts used by the LRS are usually defined as "1-in-2" probability, representing loads which will not be exceeded half the time. Extreme weather conditions may lead to loads significantly above these median estimates.

The planning activities conducted throughout the West differ from one another in their scope and purpose, but they share several essential features. All require long-term load forecasts for the region and/or for individual utility service territories. All require a projection of future generation supplies, their location in the network and their performance characteristics (e.g., heat rates, efficiencies and availability) and some characterization of the transmission infrastructure and the transmission transfer capability between regions.

4.2 Planning and Climate Variables

Electric system planning often takes place in an abstract space consisting of load bubbles and supply nodes linked by transmission lines. To make a connection with climate, the basic requirements are to situate these elements in physical, geographic space, define the time horizons associated with forecasts of load and generation, and make explicit any assumptions about environmental operating conditions during the analysis period. These can then be related to climate-driven changes in weather that may act at similar spatial and temporal scales.

Weather phenomena show non-random spatial patterns, due both to geography and to the average behavior of atmospheric and ocean currents. These spatial correlations can be active at all time scales, so that it is not necessarily true that extreme weather is localized in space as well as time. A preliminary analysis of historical data for extreme temperatures within the existing WECC control areas suggests that there are definite correlations between different areas [8], or equivalently, that heat waves tend to occur in particular spatial patterns. These patterns can have a strong impact on system reliability, as they may simultaneously increase local peak loads and decrease the potential availability of supply resources.

A graphic representation of the spatial and temporal horizons of planning activities and climate phenomena is presented in Figure 1. Spatial scales are indicated on the horizontal axis and time scales along the vertical axis. The organizations involved are categorized schematically according to the spatial scale they cover. Planning areas are typically the smallest scale region,

[9] The LRS uses a transportation model of the transmission system, which includes only connections and path ratings. TEPPC studies model the full system including power flow characteristics [56].

although they cover a wide range of spatial sizes and in some cases may be quite large. Control areas (or Balancing Authority areas) are regions within which operation of the electric grid is the responsibility of a single organization. Reliability regions are defined at the scale of the full interconnect. Each type of organization participates in a variety of planning activities. This is indicated in the body of the figure, where different activities are placed according to the typical time horizon and spatial scales they cover, and color-coded to indicate the organizations that may be involved. At the right, weather phenomena likely to be affected by climate change are listed according to their intrinsic time scales. Trends in average weather variables (such as increasing mean summer temperature) are observable, in the sense that the trend can be distinguished from year-to-year variability, over periods of roughly ten to twenty years. Persistent weather patterns act on time scales of one to a few years. These patterns are related to large-scale ocean and atmospheric currents (e.g., El Niño), which have an intrinsic dynamic but are also influenced by changing climate. Extreme weather events occur over very short periods. While the causal factors leading to any particular extreme event are difficult to predict, statistical analysis can be used to estimate the degree to which the frequency and intensity of extreme events may be affected by climate change.

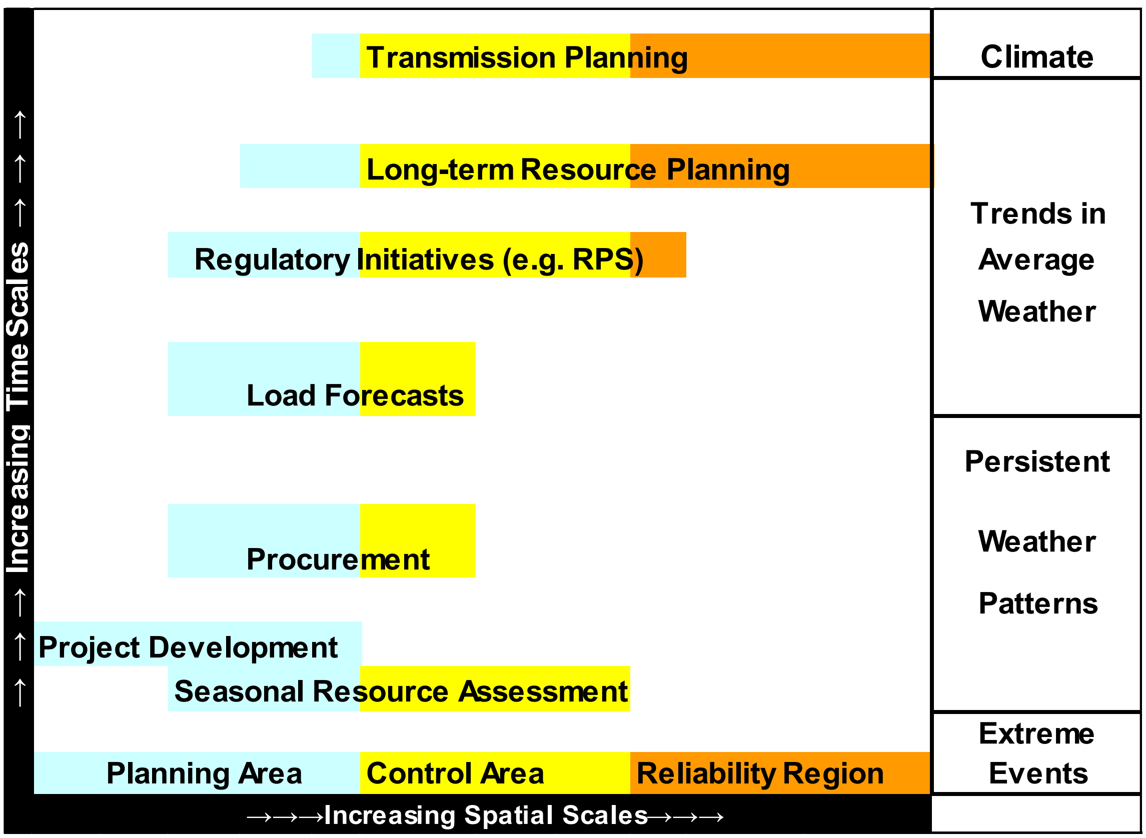

Figure 1. Schematic of the distribution of planning activities across spatial and temporal scales

When the time scale of a weather phenomenon is comparable to the time horizon for a planning activity, it may be important to include climate change impacts in the analysis. For example, drought is a persistent weather pattern with a typical time scale of one to five years that may be exacerbated by climate change [36, 37]. At this time scale, changes to the expected pattern of drought could affect generation project development, procurement, and seasonal resource assessments. The important physical parameters (as outlined in Table 1) are the availability of water for cooling of thermal plants and hydropower generation, more stringent environmental constraints on hydropower operations, and increased loads due both to higher heat levels and to increased use of energy to maintain water supplies. Project development may be affected because reduced reliability can change the economics of a given project. Procurement may be affected through, for example, increased risk that owners of water-using generation resources will not be able to fulfill long-term supply contracts. Seasonal resource adequacy assessments would need to account for the increased likelihood or persistence of drought conditions.

The structure apparent in Figure 1 also suggests a way to organize the development and maintenance of tools and databases that can be used by all planning entities. An organization at the regional scale would be a logical place to begin in terms of defining the scenarios and downscaling analyses that are most relevant to electricity planning. Other organizations engaged in electric system planning for smaller regions could use different scenarios as appropriate. Using shared data and established protocols for downscaling climate variables will help ensure that correlations with surrounding areas are correctly represented. This approach could actually lead to a substantial savings in time and effort, as it would avoid the duplication of labor that must otherwise occur if each interested party conducts their own impacts analysis. Such an approach also guarantees that consistent assumptions are used by everyone involved in electric system planning over a given geographic area, which in turn enhances the usefulness and credibility of the analysis results.

5. Incorporating Physical Climate Risk into Planning

Climate model predictions can be used to determine if systematic changes to local weather patterns are likely to occur. In this section we outline some potentially useful approaches to bringing this data into electric resource planning analysis. The main technical problem is to define a quantitative relationship between climate variables and electric system variables or operating parameters, and establish thresholds of acceptable values for the latter. Best estimates of the likelihood that climate variables will take on given values in the future can then be used to assess the probability that the power system would be pushed into a region of unacceptable risk. The details of how to do this depend on the application; in this section, we illustrate the ideas using three examples.

The first example is motivated by the possibility of extreme weather events that last longer and are more intense than past experience has led people to expect, and how these can result in electric system problems.[10] Prolonged stress can lead to failure of more than one system component, especially when several components are vulnerable to the same type of weather event. While examining the full range of possible multiple failures is not practical, climate information and system engineering parameters can be used to evaluate which conjunctions are most likely and would have the most significant impacts.

[10] The news stories cited in Section 1 are all related in some way to extreme weather.

The likelihood that different system components will experience weather-related problems simultaneously is related to the degree to which each individual problem is aggravated by a given weather event, such as an extended drought. This concept is illustrated in Figure 2. In this figure the list of system components provided in Table 1 is repeated along the rows and columns and entries in the table indicate the degree to different components are likely to be vulnerable during the same weather event. Degree is defined as low, medium or high and components with no relation are noted as not applicable (N.A.).This table is a first approximation to a correlation matrix for system problems, where the correlations are induced by how a given physical variable influences each system component. As the matrix is symmetric, only the bottom portion is labeled explicitly.

Climate Impact	Seasonal energy use	Peak demand	Load duration curves	Hydro production	Thermal plant efficiency	T&D equipment	Air quality	Import-export patterns	Coastal Infra-structure
Seasonal energy use									
Peak demand	med								
Load duration curves	high	low							
Hydro production	med	high	N.A.						
Thermal plant efficiency	N.A.	high	N.A.	high					
T&D equipment	low	med	med	high	high				
Air quality	med	high	med	high	high	N.A.			
Import-export patterns	high	high	med	high	med	low	N.A.		
Coastal Infra-structure	low	low	N.A.	N.A.	low	med	N.A.	low	

Figure 2. Matrix illustrating the likelihood of simultaneous problems to different system components due to correlations induced by weather

The correlations illustrated in Figure 2 are illustrative and not based on actual calculations. They represent reasonable extrapolations of how a given weather event could lead to several simultaneously occurring problems.[11] For example, reading across the row labeled "thermal plant efficiency" shows a high correlation with peak demand, hydro production, transmission and distribution (T&D) equipment and air quality. This is induced by the fact that all of these system components are affected both by high temperatures and/or by drought conditions. Thermal plant efficiency is moderately correlated with import-export patterns because simultaneous problems

[11] The table entries reflect probabilities, and are not related in any way to the possible severity of an event.

in these two system components are likely only in an extended drought. The correlation between thermal plant efficiency and coastal infrastructure is low because this conjunction only applies to thermal plants actually located near the coast. To move from this qualitative picture to a qualitative estimate of risk requires a more detailed calculation of how the relevant system parameters depend on climate variables.

The second example illustrates in more detail how climate data can be used to develop estimates of the increased risk due to adverse weather (this presentation follows the approach introduced in Jones [20]). A situation that is likely to be of concern for summer-peaking regions in the West is a combination of high temperatures which increase loads, and drought conditions which lead to a reduction in available generation supply (either of hydropower, or of thermal generation due to a lack of cooling water). It would thus be very useful to know if climate models routinely predict simultaneously hotter and dryer weather.

This situation is represented in Figure 3, which shows three plots. In each, the horizontal axis is seasonal average temperature and the vertical axis is seasonal total precipitation, averaged across a given geographic region. In the plot on the left, color coding is used to draw a “system risk map.” A risk metric (e.g., the magnitude of demand relative to available supply) is plotted as a function of the two climate variables. Good conditions are shown in blue (i.e., low temperatures, plentiful water), and critical conditions in red. The borders between the various colored regions represent thresholds, beyond which particular measures might need to be implemented. This map is purely for illustrative purposes and does not represent actual risk for any area in the West. Creating a quantitatively accurate map of this type can be done, for example, by using regression analysis to examine the relationship between system loads, hydro supply, and temperature and precipitation from historical data.

The center and right-hand plots show the joint probability distribution function[12] for seasonal average temperature and seasonal total precipitation, with darker regions representing higher probabilities. The center plot represents historical conditions, and the right hand plot a possible future distribution constructed from climate model runs. Again, these plots are illustrative and not based on real data. The difference between the center and right hand plot illustrates the way climate change may alter historical weather patterns. In this example, the projected future climate shows a higher likelihood of a combination of low precipitation and increased temperature. Mathematically, it is straightforward to combine the joint probability distribution for temperature and precipitation with the location of the threshold boundaries in the system risk map to produce an estimate of the likelihood that a given threshold will be crossed. Comparing the historical data to the climate projections can provide an estimate of how these risks may increase over time. Even if the information available from climate models is approximate, this kind of exercise can be useful in indicating what to look for in the future.

[12] The joint probability distribution function measures the probability that two variables will take on a given pair of values at the same time. In the illustration above, the probability that both temperature and precipitation take on their median values at the same time is high.

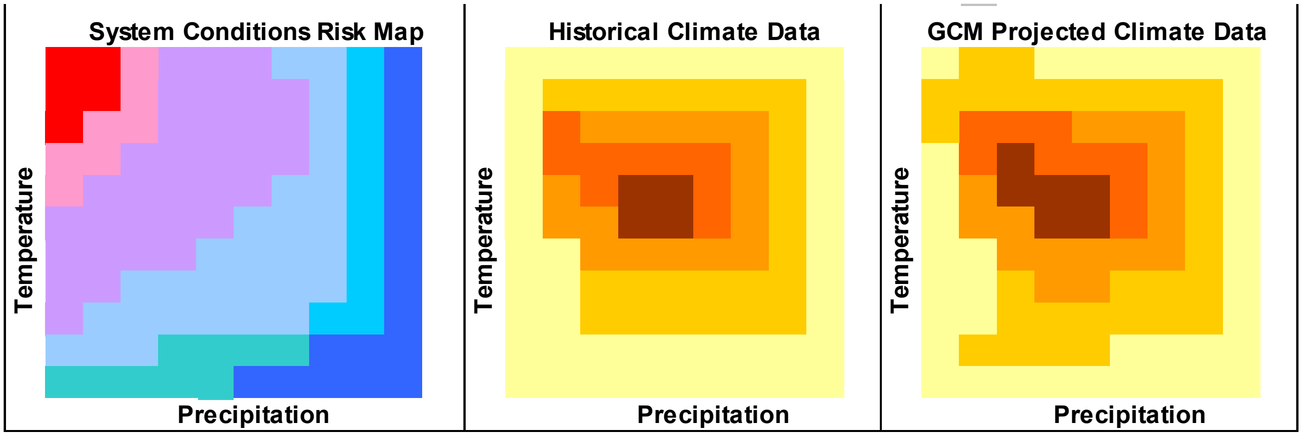

Figure 3. Illustration of an electric system risk map (on the left) as a function of two climate variables, and joint probability distributions for these climate variables based on historical data (center) and climate model data (on the right)

The third example concerns the issue of how climate influences should be represented in scenario analyses. Planning exercises are often built around a baseline scenario of business-as-usual that assumes an essentially frozen external environment. Because business-as-usual represents the situation that people are already familiar with, there may be a tendency to assume that this baseline is known with more confidence than other scenarios under consideration. This approach may become problematic in the context of changing climate. Physical science tells us that the climate is being destabilized, and it is not currently possible to predict how or when it will re-stabilize. Under these conditions, uncertainty in the baseline must be put on the same footing as other sources of uncertainty in the scenarios being analyzed. The advantage of this approach is that, once the appropriate mathematical treatment of uncertain variables is defined, it can also be applied to planning studies that are not primarily related to climate (e.g., high levels of demand response or a major shift to renewable supply).

To correctly represent the variability and irreducible uncertainty associated with climate (and other factors), the baseline scenario should be represented as a distribution. To be specific, we define the baseline in this example as the forecast of electricity loads over the analysis period in the default scenario. This definition is consistent with typical planning practice, which takes demand as given[13] and determines the supply requirements on this basis. To keep the problem tractable, only a few parameters that characterize load growth need to be treated as stochastic variables. For example, seasonal peak demand and consumption, and factors that allocate electricity use to a particular time-of-day or end use could be related explicitly to climate, based on regression analysis of historical data. Climate model data could then be used to define a probability distribution for these variables over a given future time frame. Given projected values for these variables, the more detailed representations of load that are used in system modeling can be reconstructed. This type of analysis is actually a form of statistical downscaling, and can make use of techniques that have already been developed and validated. To begin with, this

[13] Regulators are increasingly asking utilities to use energy efficiency and demand response to moderate load growth, but as yet there is no consistent representation of these programs across all utility plans [17].

approach can be used to determine in a broad sense which assumptions about the baseline are most sensitive to potential changes in climate. For example, the combination of higher peak temperatures *and* the decreasing difference between day- and night-time temperatures may lead to unexpectedly large increases in energy use for cooling. A more precise understanding of climate-related uncertainty in projections of future load can provide useful guidance on which supply- and demand-side planning options will have the highest value in reducing risk.

In several recent reviews, LBNL has looked at how utilities incorporate energy efficiency [18], requirements for generation from renewable sources [3], and regulatory risk associated with carbon emissions [1] into utility resource plans. These studies also note the importance of clearly defining the baseline against which the efficacy of proposed changes are to be measured, and finding ways to assign value to strategies that reduce risk of various kinds. The implementation of many different types of programs could be enhanced by improving the quantitative treatment of risk in analytical work. In this sense, climate risk is no more difficult to account for than other sources of uncertainty that arise in the real world.

6. Conclusions and Recommendations

This scoping study has attempted to provide the reader with some understanding of what can be learned from climate science at present and how to use the information to incorporate adaptation to potential climate change into electric resource planning. Our understanding of the climate system is evolving rapidly, and there is growing evidence that significant changes to climate will have real impacts in the relatively near future. Policy discussions have focused to date on the development of new technologies and economic incentive programs to reduce GHG emissions. This perspective assumes mitigation is distinct from adaptation, but in practice the necessary actions and their consequences are not separable. In particular, estimates of the emissions limits that constitute a safe or acceptable level of risk are likely to change repeatedly over the next few decades. Mitigation goals are thus a moving target, and in themselves constitute one of the elements that the electric power system will have to adapt to.

We have argued that the existing methods of analysis used in planning can be extended to encompass the uncertainties related to future climate, and provide concrete guidance on how to define and respond to potential climate risks. The same methods can be applied to other policy options that involve a high level of uncertainty, leading to a better understanding of system risk in general. A closer look at physically-based risk will also help clarify the distinction between the variables that describe policy choices *vs.* those that are determined by physics and engineering. This distinction is crucial, as policy variables represent the knobs that can be turned to adapt to changing physical conditions.

Several examples have been given to illustrate specific approaches to quantifying climate risk. These methods are conceptually well-defined, although significant additional work would be needed to produce quantitatively meaningful results. However, with some organizational effort, we believe that analysis of physical risk can be incorporated into the existing electric system planning framework and will provide significant benefits. Taking a regional approach to the definition of scenarios and the development of downscaling methods could greatly reduce the duplication of effort and therefore allow planning resources to be used more efficiently.

We conclude with some suggestions on how to build up the data and modeling resources that will be needed to incorporate physical climate risk into electric system planning.

- Both electric system planners and scientists engaged in climate impacts modeling would benefit from increased discussion and collaboration on specific analyses. Input from electric system experts could be very helpful in defining new climate model experiments and in developing new regional-scale data sets. Existing venues, such as the Project for Climate Model Inter-comparison and the North American Regional Climate Change Assessment Project, could serve as an initial forum for increased interaction between resource planners and climate modelers.

- In the near term, the development of public data sets and modeling tools can help to reduce the duplication of labor and encourage electric system planners to use climate data in their modeling exercises. The TEPPC Data Work Group and Studies Work Group are already engaged in compiling public databases for loads, generation and transmission resources [56]. Climate-related datasets and tools that could be similarly organized include:

    - Historical weather data and AOGCM simulation data for the Western US
    - Downscaled AOGCM time series data developed for specific studies
    - A library of quantitative engineering models that relate climate or weather variables to parameters describing electric system components.

- In the medium term, new tools and data sets could be developed specifically for analyzing climate risk in electric system resource planning. Some useful first steps would be:
    - Following the TEPPC initiative to develop a GIS-based dataset of generation resources [56], create an explicit geographic description of the regions assigned to the load bubbles used in network models.
    - Define the distribution of expected future climate conditions in the Western US to be used in impact studies. This involves choosing a representative set of emissions scenarios and climate model runs, and specifying the method used to combine the results from individual model runs into a probability distribution. The choice of models and emissions scenarios can be periodically reviewed and updated as needed.
    - Develop an open source archive where the input and output data created for specific analyses by different planning organizations could be accessed by other analysts. Over time, this should reduce the amount of time and effort needed to conduct and validate the analyses.

    - Provide guidance on how to construct load forecasts and develop coincident peak load estimates that could be used by system planners working in different geographic sub-regions. This activity may benefit from interaction with planners working on energy efficiency and demand response programs. It may also reduce the effort required by WECC staff or others engaged in transmission planning to build up self-consistent representations of the entire electric system.

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